

ELECTRONIC FUNDAMENTALS

THEORY LESSON 24

AUDIO—POWER AMPLIFICATION

- 24-1. Audio Power
- 24-2. Impedance Matching
- 24-3. Single-Ended Class A Power Amplifiers
- 24-4. Detailed Operation of Output Amplifier
- 24-5. Push-Pull Amplification
- 24-6. Phase Inverters



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Theory Lesson 24

INTRODUCTION

The purpose of this lesson is to give you an understanding of power amplifiers, so that you will know how they differ from voltage amplifiers, how you may combine a voltage amplifier with a power amplifier to produce the quality and quantity of sound that you desire, and, most of all, what you may expect from different types of audio power amplifiers.

There is a wide variety of power amplifiers and they may be classified in several different ways. They can be grouped according to their operation: audio power amplifiers may operate class *A* (like audio voltage amplifiers), class *AB*, or class *B*. Audio power amplifiers may be classed by the number and circuit connection of power amplifier tubes. Some are *single-ended*, which means that there is a single output tube between the voltage amplifier and the load (loudspeaker). Some use two tubes connected in parallel, to increase the power output. Single tube or parallel-tube power amplifiers are operated class *A*. It is possible to operate two power tubes in *push-pull*, which is a kind of series connection. Finally, power amplifiers may be classified by the kind of tube used: triode, beam-power, or power-pentode. This lesson will tell you the most important things about each type and about the circuits that are associated with each.

24-1. AUDIO POWER

In the last lesson, you learned that a voltage amplifier produces an increase in signal voltage, which is normally delivered to a high-impedance load. In the voltage amplifier, it is the amount of voltage gain that is important. On the other hand, the

purpose of a power amplifier is to transform the signal voltage applied to its control grid into enough power to drive a loudspeaker. The loudspeaker is normally a low-impedance device and acts as a low-impedance load to the power amplifier. So, an audio power amplifier delivers power into a low-impedance load. Therefore, the voltage fed to the load is not as important as the plate-current flowing through the load. In a triode voltage amplifier, we look for high μ to produce high voltage gain. In a triode power amplifier, we look for high G_m because we want a large change in plate current for a given change in grid voltage.

We measure the output of a power amplifier in watts or milliwatts. For example, the audio-power output of a radio or television receiver may be from about 2 to 15 watts, while the power output of a small portable radio may be from about 100 to 500 milliwatts.

Distortion. However, power is only part of what we look for in a power amplifier. We want to know also how much distortion is present in the power output. In some cases, we want a minimum of distortion, even if it means a loss in power. At other times, power is more important than distortion, in which case a greater amount of distortion is allowed in order to obtain the power desired. For these reasons, tube manuals rate the power tube not only according to the maximum amount of power output but also according to the percentage of total harmonic distortion that is present in the output. For example, the 3S4 power pentode, operating with 90 volts on the plate and its filament sections series connected, has a maximum-signal power output of 235 milliwatts with 13-percent total harmonic distortion. The 6L6 beam-power tube, with 250 volts on plate and screen

grid has 6.5 watts output with 10 percent total harmonic distortion. About 5% total harmonic distortion is usually considered allowable, except in high fidelity work, where the total harmonic distortion is kept to a much lower value. The power output for a particular tube, operating at some voltage other than those listed in the tube manual, may be calculated, as you will see shortly.

Plate Efficiency. Not all the power handled by a power amplifier is useful power — not all of it is delivered to the load. The no-signal plate current (I_b) produces no sound in the speaker although it produces heat in the tube. Even with a signal voltage applied to the grid, the power delivered by a class A amplifier to the load is a small part of the power fed to the tube. The power that is fed to the tube by the B-power supply, less the signal power fed to the load, represents a power loss, which we call plate dissipation. One way in which we compare the operation of power tubes is by the percentage of plate efficiency, which is a measure of what part of the total power fed to the tube by the power supply is actually delivered to the load in the form of a-c power. The formula for plate efficiency is:

$$\% \text{ plate efficiency} = \frac{\text{power out}}{I_b \times E_b} \times 100$$

In theory, the maximum plate efficiency of a class A amplifier is 50 percent. In practical class-A amplifiers, plate efficiency ranges from about 10 to 30 percent, with triodes generally having lower efficiency ratings than pentodes or beam-power tubes.

Power Output. The power output delivered to the load by a power amplifier circuit is equal to the product of the a-c voltage produced across the load and the a-c current variations through the load. An important consideration in power amplifiers is to get as much power output as possible for a given input voltage signal and d-c input power from the power supply, and with a certain maximum allowable distortion.

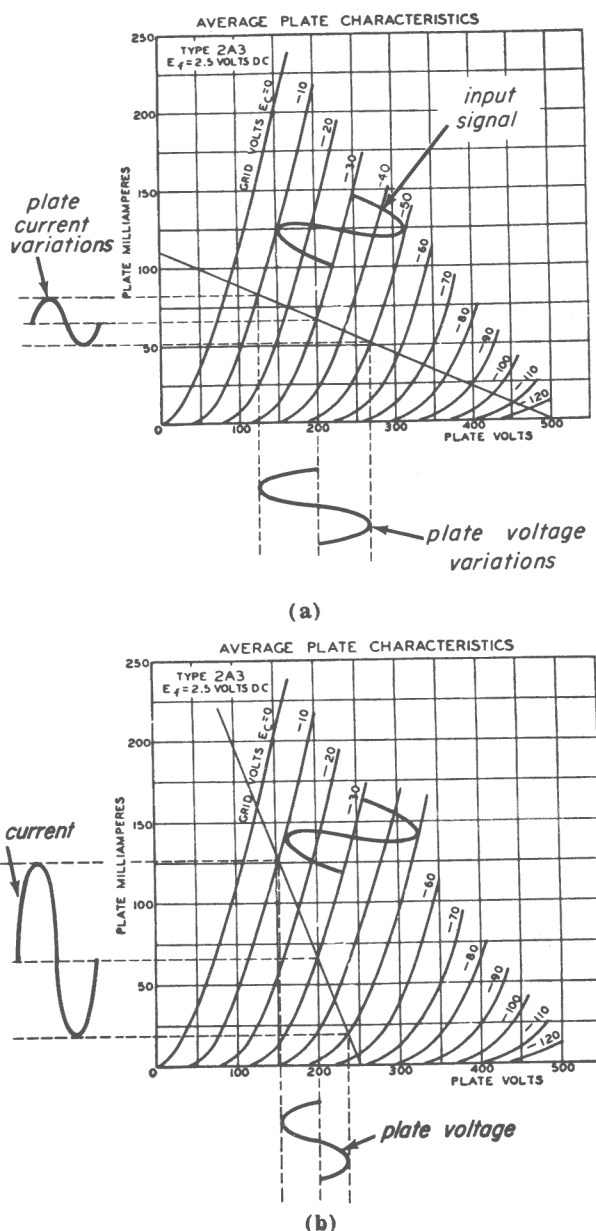


Fig. 24-1

In our study of voltage amplifiers, it was shown that the voltage gain and voltage output of a voltage amplifier increased with increasing load resistance. The power output of a power amplifier is also related to the value of plate load resistance. However, unlike the voltage output, the power is a maximum at some intermediate value of load resistance. The reason for this can be seen from Fig. 24-1, which shows two load lines drawn on the plate characteristic curves of a 2A3 power tube. For any input signal, the plate current variations and plate voltage variations are obtained from the points of intersection of the load line with

the instantaneous plate current curves. The load line in *a* of the figure is almost horizontal, corresponding to a very large value of load resistance. In this case, the plate-voltage variations are very large, but the current variations are very small and the product of the voltage and current gives a low power output. The a-c power in the load (power output) is equal to the rms values of the a-c signal voltage times the a-c signal current. The amplified voltage, when taken from a load line, equals $e_b \text{ max} - e_b \text{ min}$, and the signal current $i_b \text{ max} - i_b \text{ min}$. These are peak-to-peak values. To obtain the correct output power, we use this formula:

$$P_o = \frac{(e_b \text{ max} - e_b \text{ min}) \times (i_b \text{ max} - i_b \text{ min})}{8}$$

On the other hand, the load line shown in *b* of the figure is almost vertical, corresponding to a small load resistance. Here, for the same input signal, the plate current variations are very large, but the plate voltage variations are very small, and again the power output is low. It can be seen from the figures that some intermediate value of load resistance, which produces a slope intermediate between that of *a* and *b*, will result in maximum power output. It can also be seen from the figure that tubes for power amplifier use must be capable of handling high currents. They should also have a high transconductance — that is, the input voltage should produce large plate-current changes.

The value of load resistance which gives maximum power output is related to the plate resistance of the tube. *This relationship is different for triode and pentode tubes.* This topic will be discussed in more detail later in the lesson.

The value of the load resistance also is important in determining the amount of distortion in the output of the tube. This can also be seen by referring to the diagrams of Fig. 24-1. Here it should be noticed that the spacing between the various curves is not equal for equal changes in grid voltages. (This was ignored in the previous discussion for clarity.) This is the basic cause of dis-

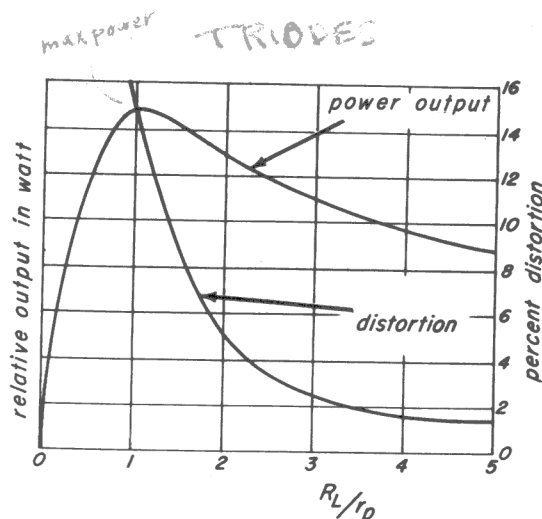


Fig. 24-2

tortion in the output. Because of this unequal spacing, the slope of the load line determines the amount of distortion in the output. Again, the results are considerably different for triodes and pentodes.

In Fig. 24-1*b*, a fairly steep load line is drawn corresponding to a low value of load resistance on the plate characteristic curves for a triode tube. It can be seen that the resulting distortion is considerable (positive swings different from negative swings). When a more horizontal load line, corresponding to a larger value of load resistance, as shown in *a* of the figure, with the same input signal, the distortion is reduced. For triode tubes the distortion decreases as the load resistance is made larger. This variation is summarized in Fig. 24-2.

It can be shown that maximum power output is obtained from a triode power amplifier when the load resistance is made equal to the plate resistance of the tube. The variation of power with load resistance is also shown in Fig. 24-2. However, this condition usually calls for a relatively low resistance, and as mentioned above, results in rather high distortion. When the load resistance equals the plate resistance of the tube, the power output is maximum, but the distortion is about 15%. This much distortion would be very disturbing to the ear. About 5% distortion is considered to be the maximum allowable for the average radio receiver. Thus, it

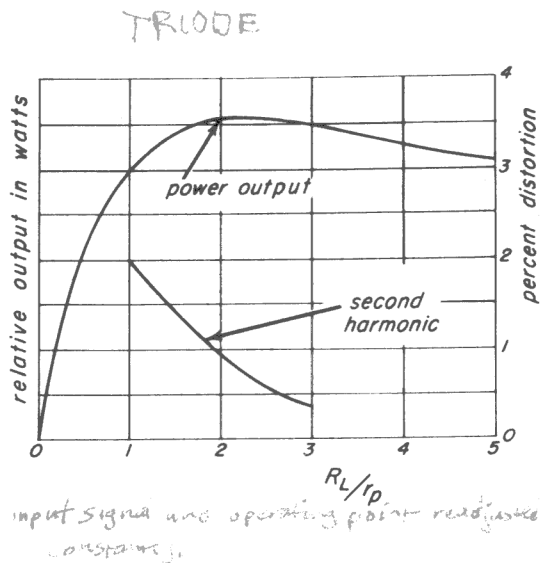


Fig. 24-3

can be seen from the figure that the load cannot be made equal to the plate resistance because excessive distortion is produced.

If the input signal and operating point are readjusted constantly as necessary to limit the distortion to a maximum of 5%, it can be shown that maximum power occurs when the load resistance is twice the plate resistance. The variation of output power with variations in load resistance under these conditions is shown in Fig. 24-3. It can be seen that the maximum is quite broad, and that the power output does not fall off rapidly even when the load resis-

tance is made three times the plate resistance of the tube. Since the distortion is lower, as the plate load is increased, many designs use load resistances that are more than twice the plate resistance of the tube. The power maximum at $R_L = 2 r_p$ shown in the figure is sometimes referred to as maximum undistorted power output. This phrase appears often in radio literature. Since power amplification cannot be obtained without some distortion, what the phrase really means is maximum power with a certain low maximum of allowable distortion. If this distortion can be neglected, we can say maximum undistorted power output.

The above rules do not apply to pentode output tubes. This is because the characteristic curves of pentodes are considerably different from triode curves, mainly because the plate current is relatively independent of the plate voltage. A typical set of plate-characteristic pentode curves is shown in Fig. 24-4. For a pentode output tube the distortion is a minimum at some intermediate value of plate-load resistance. The second-harmonic distortion is minimized when the positive swings of plate current equal to the negative swings of plate current. Three load lines are plotted on the curves of Fig. 24-4,

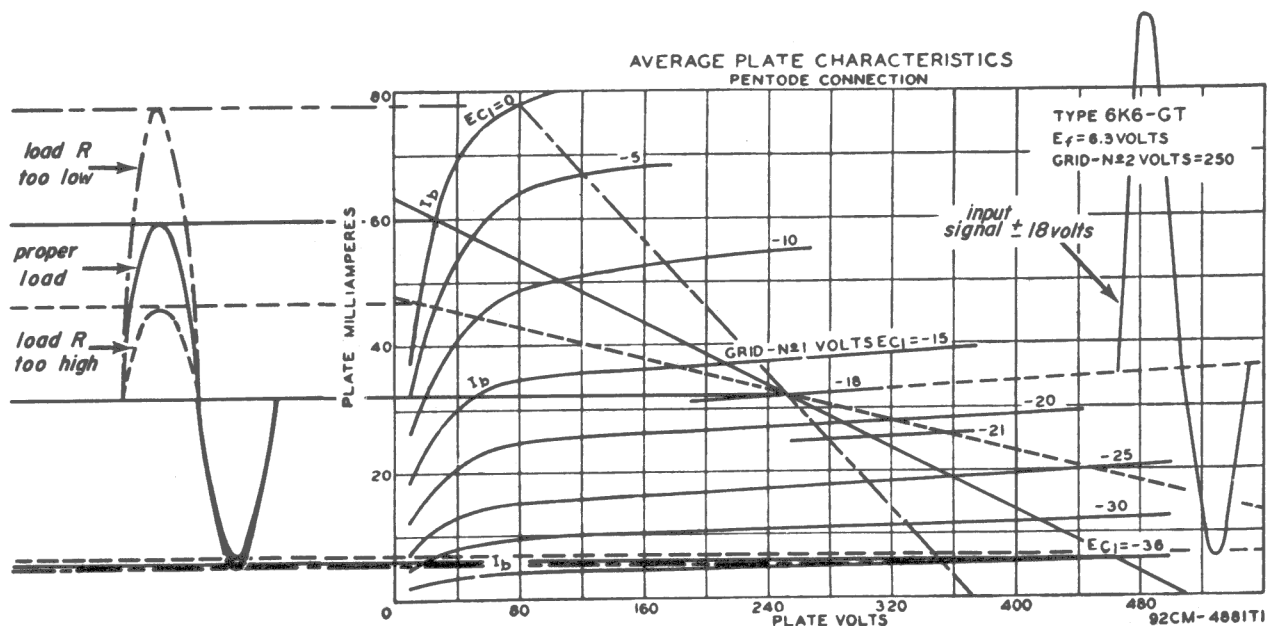


Fig. 24-4

and the resulting plate current corresponding to each one when the same signal is applied is shown. It can be seen that, when the load resistance is too low, the positive swings are greater than the negative swings, and, when the load resistance is too high, the positive swings are smaller than the negative swings. Each one of these conditions gives rise to considerable distortion. When the slope of the load line is such that it intersects the zero bias curve at the proper point, the positive swings are equal to the negative swings, and the distortion is minimized. The value of the load resistance is determined from this load line.

Although the load resistance determined in this way makes the second-harmonic distortion minimum, we must see how variations in the load of a pentode output tube affect the *total* harmonic distortion produced. This can be seen in Fig. 24-5, which shows that minimum total distortion occurs at a value of load resistance that is somewhat lower than that which gives lowest second harmonic distortion. Note also that maximum power output is produced at the same load that gives minimum total distortion. The load

resistance is about 8,000 ohms, which is much lower than the plate resistance of this tube, which is 68,000 ohms. The figure also shows how the third harmonic distortion in the output of the pentode varies as the load is changed. Even small amounts of third harmonic components are disturbing to the ear. In push-pull amplifiers, which you will study later, the second harmonic distortion is eliminated by other means. Then the load resistance may be made smaller than the value that gives minimum total distortion, so as to reduce the third harmonic distortion.

For any particular amplifier, the choice between triode and pentode power tubes depends upon the desired power output, available signal, maximum permissible distortion, and available d-c power from the power supply. Pentode power amplifiers have a greater power sensitivity; that is, they produce greater power output with a given input signal or the same power output with a much smaller input signal, than triodes. They also have greater plate efficiency, that is, they require less input power from the power supply for a given output power. On the other hand, they produce much greater distortion than triode power amplifiers. However, with proper feedback circuits the distortion of pentodes can be reduced until their distortion compares well with that of triodes. These feedback circuits are critical as to design and adjustment.

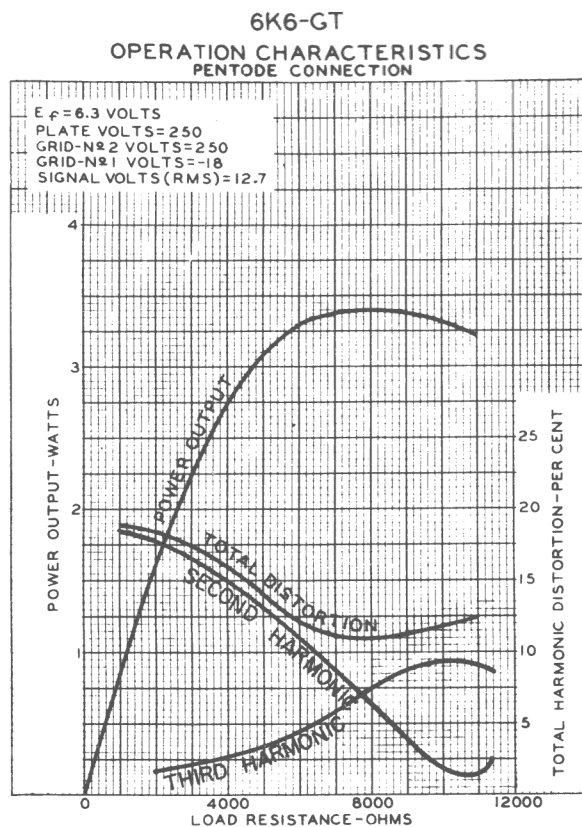


Fig. 24-5

24.2. IMPEDANCE MATCHING

The usual load for a power amplifier is a loudspeaker, which is a low-impedance device. The impedance of the voice coil of a typical speaker used in a radio or television receiver is about 3 ohms. As described in the previous section, an output tube requires a load of several thousand ohms. If the voice coil were connected directly into the plate circuit, it would produce a mismatch that would result in high distortion and poor power transfer in the output. As a typical example, let's suppose that we want to load a 6F6 power pentode to a speaker with a 3-ohm voice coil properly. Under the heading *Typical Operation*, your tube manual shows

that the proper value of load resistance is 7,000 ohms. If the tube has a load of this value, the maximum power transfer with the minimum distortion will be obtained. Our problem then is to make a 3-ohm voice coil look and act like 7,000 ohms in the plate circuit, as in Fig. 24-6. This is done with a transformer, called an *output transformer*, of the proper turns ratio.

The output transformer is an impedance-matching as well as a circuit-coupling device. We already know that the ratio of the primary and secondary voltages and currents of a transformer depend upon the turns ratio. We shall see shortly that the ratio of the primary and secondary impedances also depend on the turns ratio. Let's think this out and see why it should be so. We'll start with something that we know. A transformer with 100 volts on the primary and 400 volts on the secondary has 5 amperes flowing in the secondary. How much current flows in primary? To find the answer we use the formula:

$$\begin{aligned}\frac{I_p}{I_s} &= \frac{E_s}{E_p} \\ I_p &= \frac{E_s \times I_s}{E_p} \\ &= \frac{400 \times 5}{100} \\ &= \frac{2,000}{100} \\ &= 20 \text{ amperes}\end{aligned}$$

Now we can find the impedance of the primary and of the secondary. We use Ohm's law for a.c.:

$$Z = \frac{E}{I}$$

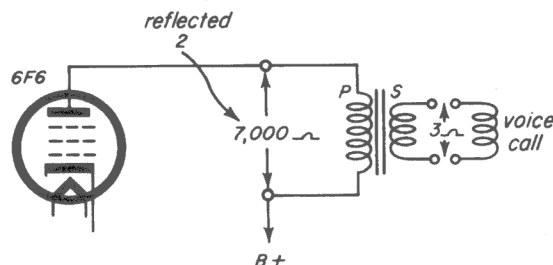


Fig. 24-6

So, the impedance of the primary is:

$$\begin{aligned}Z_p &= \frac{E_p}{I_p} \\ &= \frac{100}{20} \\ &= 5 \text{ ohms}\end{aligned}$$

The impedance of the secondary is:

$$\begin{aligned}Z_s &= \frac{E_s}{I_s} \\ &= \frac{400}{5} \\ &= 80 \text{ ohms}\end{aligned}$$

The turns ratio is:

$$\begin{aligned}\frac{N_p}{N_s} &= \frac{E_p}{E_s} \\ &= \frac{100}{400} \\ &= \frac{1}{4} \text{ or}\end{aligned}$$

1 : 4 (primary to secondary)

If the load resistance on the secondary were halved, the secondary current would

increase and become 10 amperes. The current flowing in the primary would have to become 40 amperes (as a moment's figuring will show). The primary impedance is then:

$$\begin{aligned} Z_p &= \frac{E_p}{I_p} \\ &= \frac{100}{40} \\ &= 2.5 \text{ ohms} \end{aligned}$$

The secondary impedance is:

$$\begin{aligned} Z_s &= \frac{E_s}{I_s} \\ &= \frac{400}{10} \\ &= 40 \text{ ohms} \end{aligned}$$

Let's see what happens when the secondary current is reduced. Let's say that $I_s = 1$ ampere. The primary current becomes 4 amperes. The primary impedance becomes:

$$\begin{aligned} Z_p &= \frac{E_p}{I_p} \\ &= \frac{100}{4} \\ &= 25 \text{ ohms} \end{aligned}$$

The secondary impedance becomes:

$$\begin{aligned} Z_s &= \frac{E_s}{I_s} \\ &= \frac{400}{1} \\ &= 400 \text{ ohms} \end{aligned}$$

Let's collect these impedance values together and see how they compare.

Secondary Z	80 Ω	40 Ω	400 Ω
Primary Z	5 Ω	2.5 Ω	25 Ω

A secondary impedance of 80 ohms produces an impedance of 5 ohms in the primary. We say that the secondary *reflected back* an impedance of 5 ohms, or simply, the reflected impedance was 5 ohms. When the secondary impedance dropped to 40 ohms, the primary impedance dropped to 2.5 ohms. When the secondary impedance rose to 400 ohms, the primary impedance rose, too. Thus, the impedance seen by the secondary depends upon what is connected across the primary, and vice versa.

We know that the secondary-to-primary turns ratio of the transformer is 4 to 1 while the impedance ratio in each of the three cases is 16 to 1. This impedance ratio is the square of the turns ratio, $(4/1)^2 = 16/1$. If we try other values, we would find that the impedance ratio is always equal to the square of the turns ratio or:

$$\frac{N_p^2}{N_s^2} = \frac{Z_p}{Z_s}$$

or:

$$\frac{N_p}{N_s} = \sqrt{\frac{Z_p}{Z_s}}$$

Let's see how we can use this formula to find the turns ratio of an output transformer that will reflect back a 7,000-ohm impedance when loaded by a 3-ohm voice coil. Let T_r stand for turns ratio; then:

$$T_r = \frac{N_p}{N_s}$$

and

$$T_r^2 = \frac{Z_p}{Z_s} = \frac{7,000}{3} = 2,333$$

$$T_r = \sqrt{2,333} = 48 \text{ to } 1 \text{ (approx)}$$

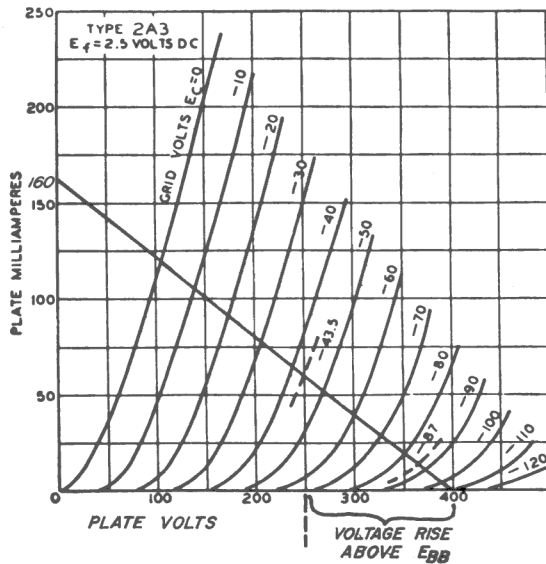


Fig. 24-7

Therefore, for every turn in the secondary winding, the output-transformer primary winding will have 48 turns. With a transformer having a 48 to 1 turns ratio, the 3-ohm load in the secondary acts like a 7,000-ohm load in the primary. In this way, the output transformer becomes an impedance-matching device.

When an inductance, such as the primary of the power transformer, is used as the plate load of a tube, the plate voltage with no signal input is practically equal to the B+ supply voltage because there is no drop across the low d-c resistance of the primary winding. When signal is applied to the tube, the voltage at the plate of the tube rises above the plate-supply voltage on the negative swings of the input signal, as shown in Fig. 24-7. This situation is different than the case with a resistive plate load, where the plate voltage is always less than the B supply voltage. The plate voltage rises above the B supply because, when the plate current is decreasing, the inductive voltage drop across the primary is of the polarity shown in Fig. 24-8, which adds to the B supply voltage.

24-3. SINGLE-ENDED CLASS A POWER AMPLIFIERS

A single-ended audio power amplifier must operate class A in order to keep the

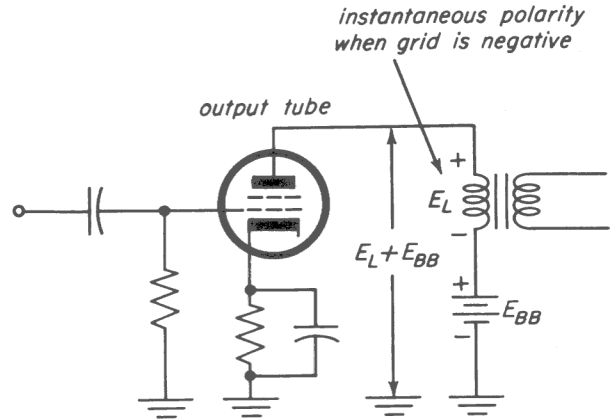


Fig. 24-8

total harmonic distortion within reasonable limits. The power amplifier must supply the a-c power necessary to drive the loudspeaker without producing a distorted output. Its input signal must be supplied by a voltage amplifier that produces a suitable voltage swing for the power-amplifier grid. Because the *driver* (voltage-amplifier) stage must meet the needs of the output (power-amplifier) stage, each must be designed with the other in mind. Because of the need for dissipating power, power amplifier tubes are usually larger and get hotter than tubes used for voltage amplification. This is understandable when you consider that a power amplifier may have 100 or more times the plate current flow that a voltage amplifier has.

Selecting A Power Amplifier Tube. The power tube may be either a triode or a pentode. (We are classifying beam-power tubes as pentodes, which, effectively, they are.) If a triode is selected and properly operated, the output will contain less total harmonic distortion and less power than would be found in the output of a comparable pentode. But the triode has less *power sensitivity* than a pentode. Power sensitivity is the ratio of the power output to the square of the input rms signal voltage. The formula is:

$$\text{Power sensitivity} = \frac{\text{output power (watts)}}{(\text{input rms signal volts})^2}$$

A triode, having less power sensitivity than a pentode, requires a greater input signal

voltage than a pentode to produce an equal amount of output power. For example, a 2A3 power triode requires a 90-volt peak-to-peak (31.8 volts rms) signal to produce a 3.5-watt output with 5-percent total harmonic distortion; while a 6K6-GT power pentode needs only 36 volts peak to peak (12.7 volts rms) to produce a 3.4-watt output. However, the pentode output has 11-percent total harmonic distortion, which is more than double the distortion of the triode.

Whether a triode can provide the power needed or whether it is necessary to use a pentode depends on how much power we need and the amount of distortion that is allowable. This in turn depends upon the size of the room in which the amplifier and speaker are used, the amount of noise that the speaker output must ride over, and the efficiency of the speaker. Speakers range in efficiency from about 2 percent to 5 percent for one of good quality. When such speakers are properly mounted in well-designed speaker baffles, the speaker efficiency ranges from 10 to almost 50 percent. This means that a poorly designed speaker, improperly baffled, requires much more power to produce a certain output sound level than is needed by a well-designed, properly

baffled speaker. A typical example shows how this works out. A large living room with about 3,000 cubic feet of space requires about one-half watt of sound power from the speaker. If the speaker has 5 percent efficiency, the audio amplifier has to deliver 20 times the needed power — about 10 watts. (Speakers and baffles are discussed fully in a lesson that you will receive shortly.)

A radio receiver installed in a small kitchen requires much less audio power than a receiver placed in a large living room; while a receiver placed in a busy office of the same size as the living room needs even greater audio power to overcome the noise level of the office. The kitchen receiver may operate satisfactorily with an electrical power output of one watt, or less; a receiver in the living room may require from 5 to 10 watts of electrical power; while the office receiver may need as much as 25 watts to maintain the same apparent sound level.

Table A compares different output tubes for plate dissipation, plate efficiency, power output. Notice that two tubes are listed twice, once for triode con-

TABLE A

Tube Type	Connection	Power Sensitivity*	D-C Power Used (watts)	Output (mw)	% Efficiency
45	triode	0.00275	11.9	2,000	16.8
50	triode	0.001305	29.3	4,600	15.7
2A3	triode	0.00346	17.7	3,500	19.8
6F6	triode	0.00400	8.4	800	9.5
6L6	triode	0.00650	10.8	1,300	12.0
6F6	pentode	0.0225	13.7	4,500	32.8
6K6-GT	pentode	0.0235	9.7	3,200	33.0
6V6-GT	beam power	0.0576	13.0	4,500	34.6
6L6	beam power	0.0664	21.2	6,500	30.6
35L6-GT	beam power	0.0539	4.7	1,500	32.0

nection and once for pentode connection. When a pentode is used as a triode, the screen and suppressor grids are connected to the plate, unless some other connection is called for. When connected in this way the pentode operates like a triode and its μ , G_m , and r_p are different than they are for pentode connection. Your tube manual shows triode operating conditions for some pentode tubes commonly used as triodes.

24-4. DETAILED OPERATION OF OUTPUT AMPLIFIER

Now that we know the basic principles underlying the operation of power output amplifiers, let's select a 2A3 triode and look into its operation as an audio power amplifier in more detail.

Of course, you can always select a tube from the tube manual that is capable of supplying the amount of power needed, and operate it by providing the signal voltages and supply voltages and plate load as given in the tube manual. However, examining how these things may be determined will increase your understanding of triode power amplifier operation.

There are a number of different ways of determining the proper operating conditions for a triode power amplifier. The method given here is chosen to emphasize basic principles.

We want to operate this tube so as to get as much power output as possible, with the distortion not to exceed a certain figure which is usually 5%. The power output is limited by the available B supply voltage, the input signal, and the amount of allowable dissipation of the tube. The circuit is shown in Fig. 24-9. We must find E_{cc} , I_b , R_L , e_g , the power output, and the amount of distortion.

As a starting point, let us assume two things: (1) We have a power supply capable of delivering 250 volts at whatever current we find to be necessary, and (2) our driver stage can be made to deliver whatever peak voltage swing we find necessary.

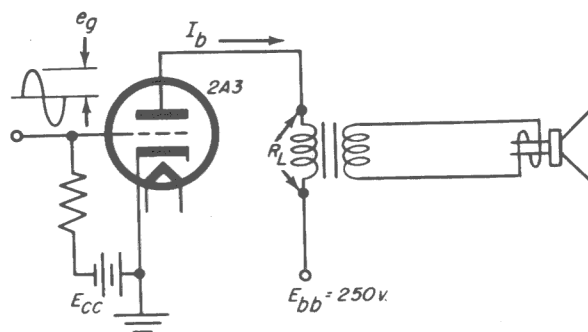


Fig. 24-9

The first thing to do is to determine the operating point for the tube, that is, the operating bias E_{cc} and the no-signal plate current I_b . Since the d-c drop in the power transformer primary is very small, we will ignore it here and consider that the plate voltage E_b is equal to the supply E_{bb} and is equal to 250 volts.

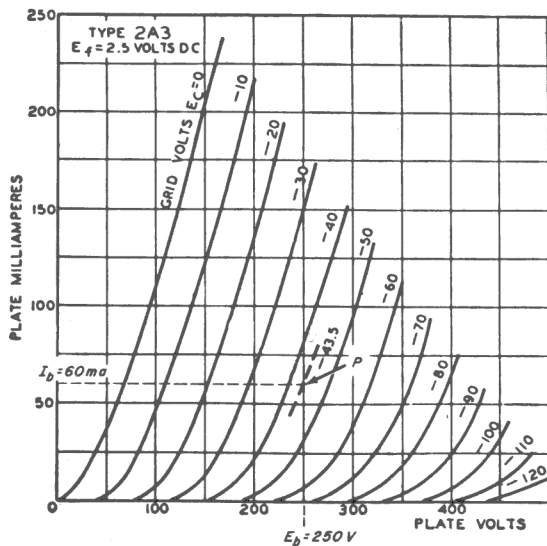
The bias should be chosen to allow the average plate current to be as high as possible, since the higher the average plate current, the greater the changes in plate current may be. But the plate current is limited by the allowable plate dissipation of the tube, which is fifteen watts. Since the plate voltage is fixed, the average plate current cannot be greater than:

$$I_b = \frac{P_{\max}}{E_b} = \frac{15 \text{ w}}{250 \text{ v}} = 60 \text{ ma}$$

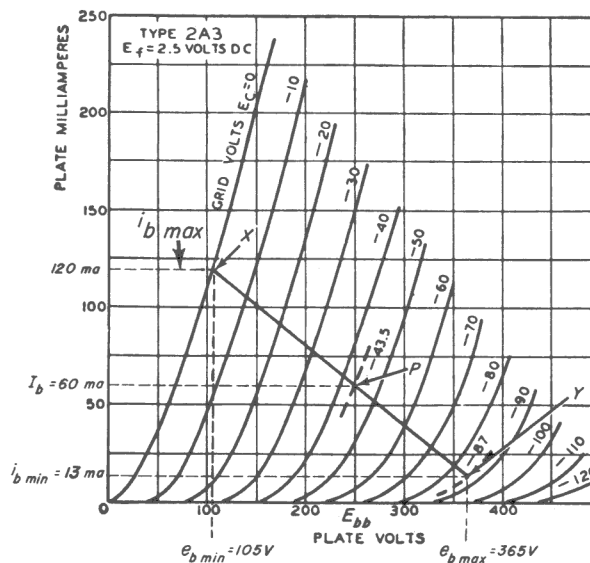
The plate dissipation may be at or near the maximum when the input signal is zero, because when signal is applied the plate dissipation is reduced. This is because part of the power is now dissipated in the load instead of the tube.

To limit the average plate current to 60 ma at a plate voltage of 250 volts, we find from the curve that the bias must be -43.5 volts. Thus we have located the operating point, at the intersection of $E_b = 250$ volts, $I_b = 60$ ma, and $E_c = -43.5$ volts. The operating point is shown as point *P* in Fig. 24-10a.

We want as much power output as possible and therefore we should drive the tube with



(a)



(b)

Fig. 24-10

the greatest signal it will accommodate. The peak signal is just equal to the bias, and the required peak-to-peak signal swing is 87 volts.

To minimize distortion, the plate load selected must prevent the most negative grid swing from reducing the plate current to a point where the operation will be in the region of extreme curvature of the plate characteristic curves. Since the maximum negative grid voltage is -87 volts, we run along the -87 volt curve (shown dashed) until we come to a region of considerable curvature and crowding. Let us assume that above 13 ma this curve can be considered straight. This is a guess, and we can only tell later whether it was right or not. Based on this assumption however, we will let the current go to a low of 13 ma, but no lower. (A minimum current that is at least 0.25 of I_b is usually about right.) The intersection of the 13 ma line with the -87 volt curve gives us one point on the load line. Since the load line also passes through the operating point, we now have two points through which the load line can be drawn. The value of load resistance needed to produce this load line is obtained from the slope of the line, using any convenient interval of plate voltage change, and the corresponding plate current change along the line. Thus the

load can be found from:

$$\frac{\text{change in } E_b}{\text{change in } I_b} = \frac{365 - 105}{(120 - 13) 10^{-3}} = 2430 \text{ ohms}$$

The load line is shown in Fig. 24-10b.

The power output can then be determined using the power output formula previously given, where the quantities $i_{b \max}$, $i_{b \min}$, $e_{b \max}$, and $e_{b \min}$ are defined on the figure. Substituting these values in the formula gives:

$$\begin{aligned} \text{power output} &= \frac{(i_{b \max} - i_{b \min})(e_{b \max} - e_{b \min})}{8} \\ &= \frac{(0.12 - 0.013)(365 - 105)}{8} \\ &= 3.48 \text{ watts} \end{aligned}$$

In the output of power-amplifier triodes, the second harmonic distortion component is the most predominant. The percentage of this distortion component may be found from the formula:

$$\% \text{ 2nd-harmonic distortion} = \frac{(i_{\max} + i_{\min})}{2} - I_b \times 100$$

When the proper values are substituted:

$$\% \text{ 2nd-harmonic distortion} = \frac{(0.12 + 0.013) - 0.06}{0.12 - 0.013} \times 100 = 6.07\%$$

The result is 6.07 percent. Since the higher harmonics are quite small in this case, we can say that the total harmonic distortion does not exceed about 6%, which is a little more than our predetermined limit.

This means that our minimum of 13 ma was a little too low, and that we should have used about 14 ma as our minimum plate current. Actually this difference is negligible, unless very large characteristic curves are available. A slight increase of load to 2,500 ohms reduces the second-harmonic distortion to 4.9 percent. Therefore we can say that we get about the same operating values as were given for the 2A3 in the Tube Manual. There is one exception: we found the grid bias to be -43.5 volts, while the value given in the tube manual is -45 volts. However, you will find that the tube manual shows that the 45-volt bias is for the tube when the filament is heated by

a.c., while our value of -43.5 volts is the grid bias when the filament is heated by d.c. When a.c. is used instead, we add about 1/2 the value of filament voltage, which is 1/2 of 2.5 volts, or 1.25 volts. This, added to our -43.5 volt bias makes a total of -44.75, which is rounded off to -45 volts, as given in the tube manual.

In the event that we want less distortion than this, we choose a higher value of load resistance, which would give us less distortion along with reduced power output, as was shown in Fig. 24-3. This corresponds to choosing a higher minimum value below which the plate current must not be allowed to go. For example a load line corresponding to 5,880 ohms drawn through the same operating point as shown in Fig. 24-11 gives about 2% distortion, but the power output is reduced to about 2.1 watts. All the data is given on this figure should you wish to calculate the output and distortion yourself.

On the other hand, if the power output is not sufficient then you must either decrease the load resistance or raise the input signal,

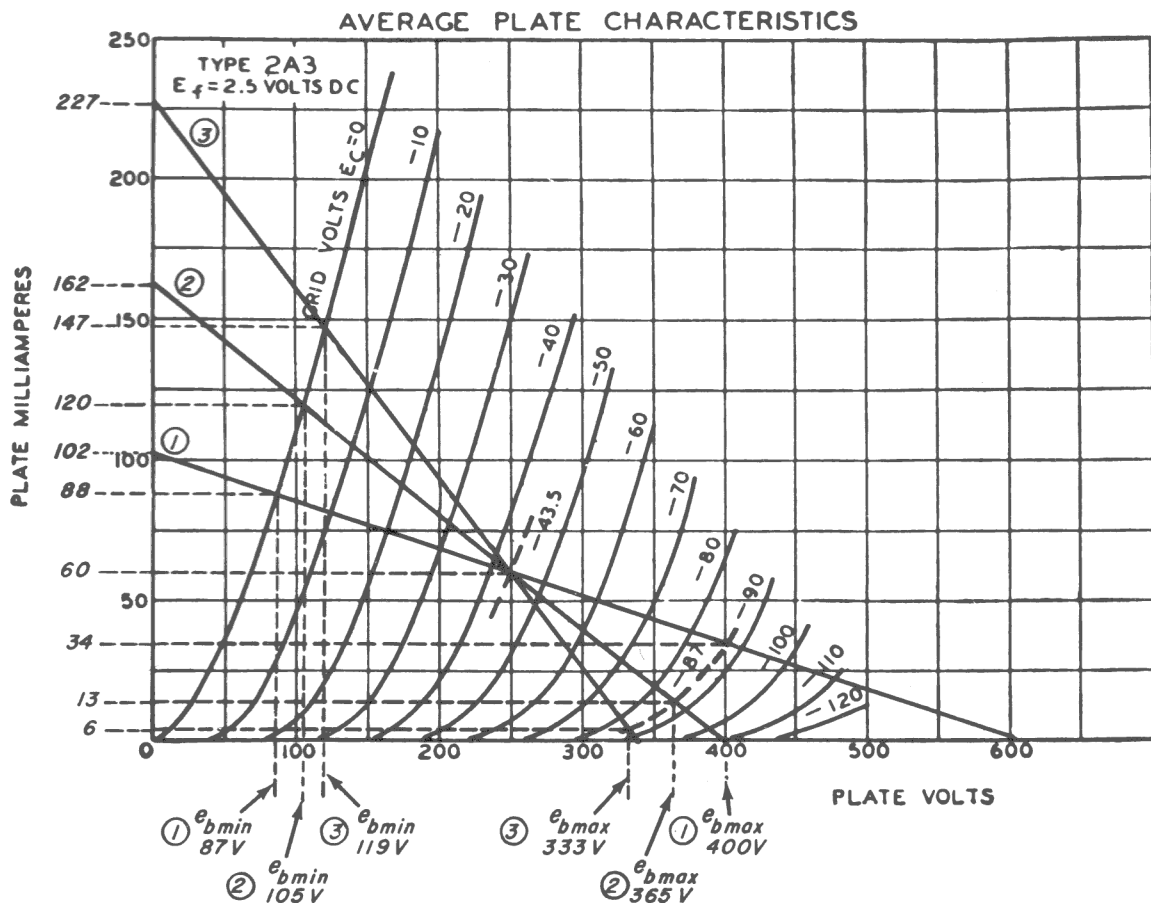


Fig. 24-11

and the $B+$ voltage if this can be done without exceeding the maximum ratings of the tube. A load line corresponding to 1,500 ohms is shown in the figure. Using this load gives an increase to only 3.8 watts, but the second harmonic distortion rises to almost 12%. Increasing the power output in this way usually produces more distortion than can be tolerated. Other methods are used when higher power outputs are desired. Some of these will be described in this lesson.

We have now discussed the determination of all the unknown elements and have actually gone through a simplified design of a triode power-amplifier stage.

Since the actual load for the output stage is a loudspeaker whose voice-coil impedance is usually about 3 ohms, the required load of 2,500 ohms in the plate circuit is obtained by using an output transformer having the proper turns ratio.

As we have said, the usual load for a power output tube is the loudspeaker voice coil. It offers a load that varies with frequency, amplitude, and other factors. However, it is considered to be a resistive load and so is said to reflect resistance back into the output transformer primary. When the

loudspeaker is coupled through the output transformer, however, it is not strictly a resistive load. This is because the transformer does not pass all frequencies with equal amplitude, and the transformer also causes harmonic or amplitude distortion, partly because the large d-c current flowing through the primary tends to produce magnetic saturation, particularly in single-ended amplifiers. However, unless the d-c resistance of the transformer primary is high, the values obtained from a load line for a resistive load are about the same as for a transformer-coupled loudspeaker. For this reason, the load lines used for obtaining operating conditions for a power amplifier are usually the same as those used for a resistive load. In such cases, E_{bb} and E_b are considered to be about the same. So, loaded by a transformer-coupled loudspeaker, the tube operates the same as if it had a resistive load of the same value, but a much larger plate supply voltage.

Pentode or Beam-Power Operation. The same general methods are used in determining the operating conditions and value of load resistance for a power pentode or beam-power tube as for a triode. As in the case of triodes, typical operating conditions for

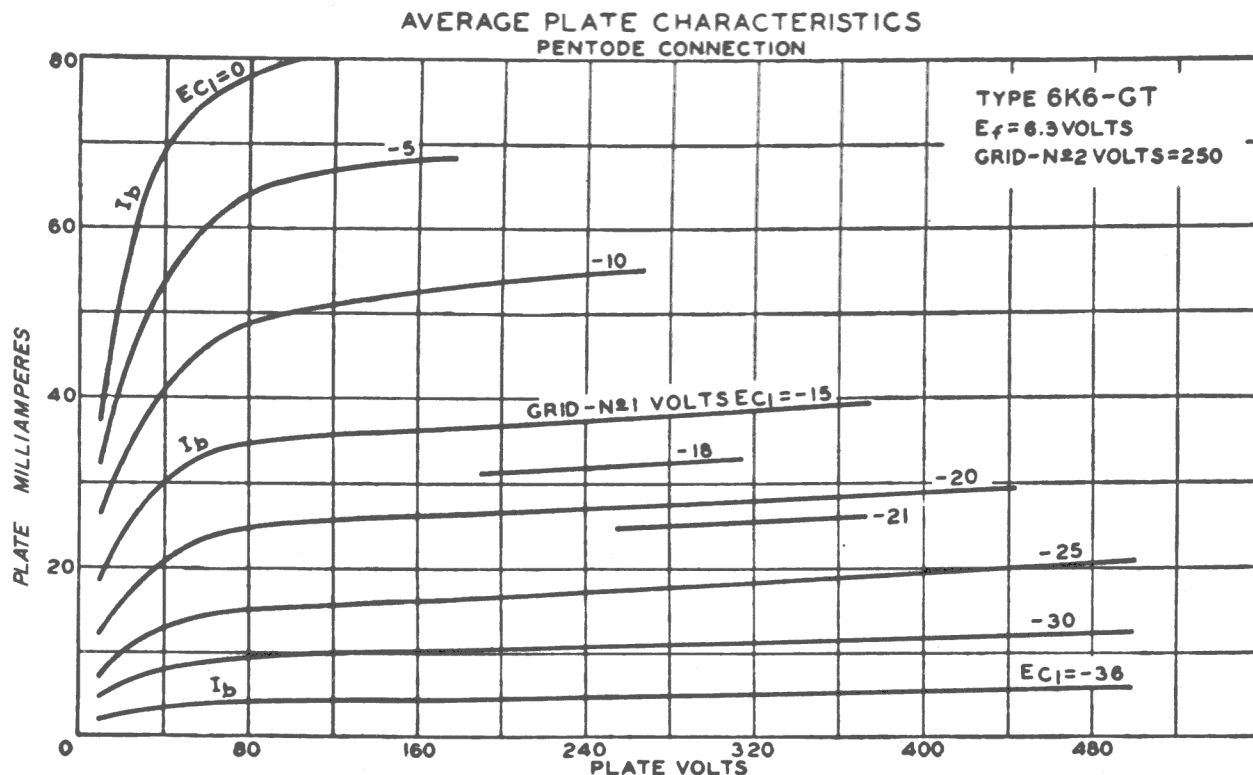


Fig. 24-12

many pentode and beam-power tubes are given in the tube manual. All you need do is pick one that can supply the power needed, and operate it with the supply voltages and plate load as suggested in the tube manual. However, your understanding of pentode power amplifiers will be increased by studying how these values may be determined.

There are a number of ways of approaching the problem of determining the proper operating conditions of a pentode by graphical analysis. The method given here is such as to emphasize the basic principles involved.

To begin with, the no-signal plate current is made as high as possible without exceeding the plate dissipation of the tube, just as in the case of a triode. For the type 6K6-GT pentode, whose plate characteristics are shown in Fig. 24-12, and, assuming a plate voltage of 250 volts, this is:

$$I_b = \frac{P_{\max}}{E_b} = \frac{8.5 \text{ watts}}{250 \text{ volts}} = 34 \text{ ma}$$

The bias needed to limit the current to 34 ma is somewhat less than -18 volts. The value of -18 volts is used, for convenience, since it is the next highest value shown on

the curves. This bias value gives the no-signal operating conditions as 32 ma at 250 volts. Also, since the peak driving signal needed is equal to the bias, the signal required is 36 volts peak-to-peak.

As a starting point for finding the required plate load, draw several load lines through the operating point, as shown in Fig. 24-13. What we are looking for is a load line that makes the increase of current when the signal drives the grid from -18 to 0 volts equal to the decrease in current when the signal drives the grid from -18 volts to -36 volts. At this condition, there will be a minimum of second harmonic distortion. Unlike triodes, the shape of the knee of the pentode curves at low plate voltages allows the positive and negative swings of plate current to be made almost equal by proper choice of load line. This will reduce the second harmonic distortion to a minimum.

The proper slope can be found by trial and error, while looking for equal lengths PA and PB along the load line or for equal current changes $i_{b\max} - I_b$ and $I_b - i_{b\min}$. A pair of dividers, or a zero-center rule having equal calibrations on each side of a mid-point can be helpful in finding the correct

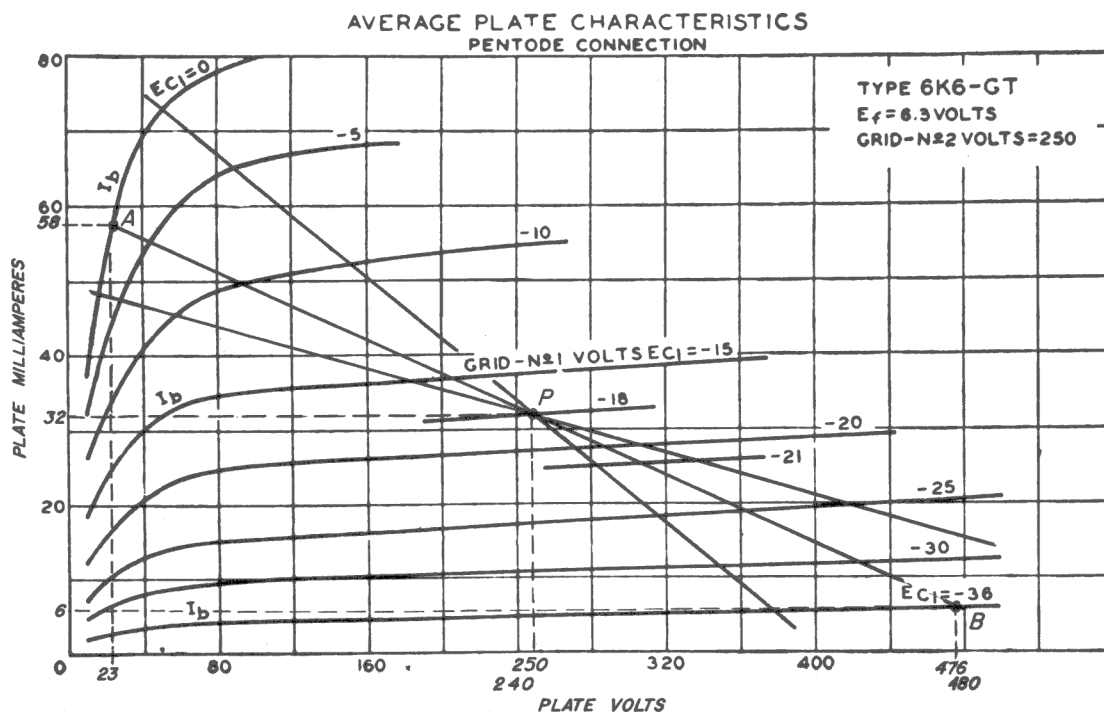


Fig. 24-13

slope. It can also be found somewhat more directly by noting that in the region where the load line is most likely to intersect the -36 volt curve, say from 200 volts to 500 volts, the -36 volt curve is quite flat and the current almost constant. Therefore, regardless of the actual point of intersection of the load line, $i_{\min}$ will be very close to 6 ma. Since the average current point I_b is known to be 32 ma, the change in current produced by the negative grid swing is 32 ma $-$ 6 ma, or 26 ma. The load line should be such that when the signal brings the instantaneous grid voltage to zero, the increase in current should be equal to the decrease. This gives $i_{\max}$ to be 32 ma $+$ 26 ma, or 58 ma. At the intersection of the zero-bias curve and 58 ma, therefore, we have a definite point for the desired load line.

Drawing a line through this point and the operating point P gives the required slope. The value of load resistance can be found by dividing $(476 - 23)$ volts by $(58 - 6)$ ma and gives about 8700 ohms. This load resistance is the correct value for minimum second harmonic distortion. Note however that this is *not* the recommended value of load resistance given in the tube manual for this tube. The reason for this is readily seen by examining Fig. 24-5. Here it can be seen that at the point where the second harmonic distortion is at a minimum, the *total* distortion is not. Minimum total distortion occurs at a lower value of load resistance, in this case at 7,600 ohms. Since the calculation of total distortion requires lengthy and tedious calculations, it is best to take the recommended value. Formulas for finding the power output and percentage of harmonic distortion are more complex than those given for triodes in the tube manual.

24.5. PUSH-PULL AMPLIFICATION

The purpose of the output stage of a radio receiver is to furnish enough audio power to drive the loudspeaker. Therefore, it is necessary to get a large power output from the tube used to drive the loudspeaker. The

power output of the output tube increases when the input signal increases.

Let's consider the 6K6, a pentode used as a power amplifier. If this tube is to deliver about 5 watts output to drive a loudspeaker, it requires an audio input of about 40 volts peak to peak. But, when the input signal is raised to 40 volts, the signal is not on the straight part of the i_b-e_c curve.

The higher the value of input signal, that is, the greater the input-signal swing, the greater the operating voltage will be, and the greater will be the portion of the i_b-e_c curve on which the tube operates. These curves are less linear at their extremes. Therefore, increased input signal means greater distortion at the output.

So, we are faced with a problem. Although we want to increase the power output of the tube by increasing the operating voltages of the tube, increasing the operating voltages increases distortion. For instance, when the output of a 6K6 stage is increased from 3.4 to 4.5 watts as a result of increasing the operating voltages, the harmonic distortion increases from 11 percent to 15 percent.

Thus the major problem in power amplification is how to obtain high power output with a reasonable amount of distortion. As you know, 5-percent total harmonic distortion is the upper limit of distortion normally allowed in audio amplifiers of good quality. In fact, high-quality audio amplifiers may have less than 1 percent harmonic distortion when operated at their normal power output levels. The tubes that provide the greater amounts of power — the power pentodes and beam power tubes — do so with relatively high distortion. Look up some output tubes in your tube manual and you'll find that a power pentode such as the 6K6 provides from 0.35 to 4.5 watts of audio power with 11 to 15 percent total harmonic distortion, and the 6L6, a beam-power tube, delivers from 6.5 to 15 watts of power with 10 to 15 percent total harmonic distortion. If we wanted to get twice the power of a single tube while using the same grid drive, we could connect two tubes in parallel. But the amount of distor-

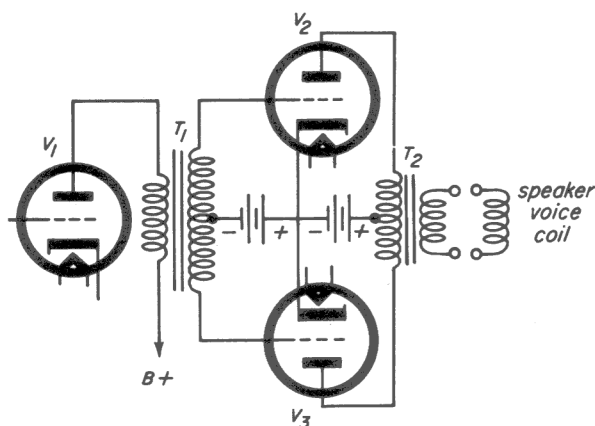


Fig. 24-14

tion remains the same as in a single tube. If we want less distortion it might seem that we are limited to triodes with their lower power output. But this is not so.

We can get more power output without increasing distortion by using a *push-pull* output amplifier such as the one shown in Fig. 24-14. Two identical tubes are connected so that they receive signals that are equal in amplitude but opposite in polarity. The audio plate currents are opposite in polarity in the two tubes. However, the tubes are connected to an output transformer so that the a-c signal currents add in the transformer. A push-pull circuit of this type provides twice the power output of a single tube with the same or less distortion than that from a single tube.

Despite the fact that push-pull operation requires twice the signal voltage needed by a single tube, it has important advantages over single-tube operation. These are:

1. Greater power output
2. Lower total harmonic distortion because even harmonics (2nd, 4th etc) tend to cancel out or be reduced
3. Less hum
4. Greater plate efficiency, particularly when operating Class AB or B
5. No magnetic saturation of the transformer core

When a triode is used as an amplifier, and $R_L = r_p$, there is harmonic distortion. Therefore, R_L must be raised to 2 to 3 times r_p .

Because even harmonics tend to cancel out in a push-pull circuit, we may reduce the value of R_L almost to the point where it equals r_p . In this way, we obtain almost maximum power transfer without increasing the total harmonic content in the output signal delivered to the load.

Let's consider the simplified circuit in Fig. 24-15 when there is no input signal. Steady, no-signal plate currents flow in opposite directions (I_{b1} and I_{b2}) in each half of the output transformer. The currents produce magnetic fields in the primary winding. The magnetic field produced by the steady plate current in the upper half of the primary winding is opposite in direction to the magnetic field produced by the steady plate current in the lower half of the winding. The current is equal in both halves, so that the resulting magnetic field due to the steady d-c plate current is zero. Thus, the core of the transformer is not magnetized. This is one of the important advantages of the push-pull circuit, because it increases the range of signal which can be handled by a transformer of given size.

Also, if any a-c ripple (hum) is present in the B-supply voltage and causes changes of plate current, the same changes will be produced in each tube. The magnetic fields produced by the plate currents for each tube will vary, but will remain equal and opposite, cancelling each other, and hum voltage will not be induced in the secondary winding.

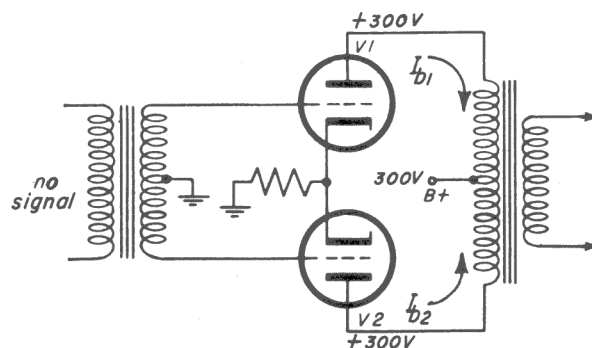


Fig. 24-15

Thus filtering of the B+ supply for the output stage is simplified. However, any hum modulated on the input signals to the grid will be amplified and reproduced in the output. Only distortion introduced by the output stage itself is cancelled by the push-pull circuit.

The total voltage across the primary of the output transformer is the difference in voltage between the plates of V_1 and V_2 . When no signal is applied, the same current flows in each tube, so that the voltage drop across each half of the output transformer is the same. (It is assumed that the tubes and output transformer are balanced.) Thus, if the supply voltage is +300 volts and the d-c voltage drop across each half of the transformer can be neglected, the voltage at the plate of V_1 is +300 volts and the voltage at the plate of V_2 is +300 volts. The voltage between the plates is zero. There is no voltage difference across the primary output transformer and no output.

Now, let's consider what happens with an applied signal, as shown in Fig. 24-16. If a signal is applied to the tubes that makes the grid of V_1 positive-going, for example, the grid of V_2 will be negative going during the same interval. The plate current of V_1 will increase. Since the current through the top section of the transformer is increasing, an a-c voltage drop will now appear across the top half of the transformer with the polarity as shown in the figure. The polarity is as shown because, whenever current tries to increase through an inductance, the voltage induced by the changing current across the inductance is in a direction that opposes the increase in current.

Let us say that the peak value of this a-c voltage is 50 volts. Since its direction is such that it opposes the B supply voltage, it will cause the plate voltage to go to a low of 250 volts. At the same time, the current through the bottom half of the transformer is decreasing, at the same rate, and the peak voltage will also be 50 volts, but with the opposite polarity as shown in the figure. Thus, while the voltage at the plate of V_1

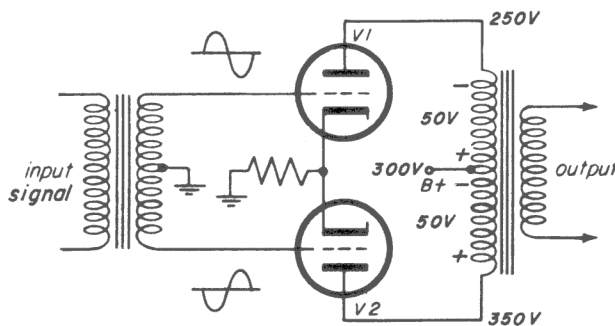


Fig. 24-16

has fallen to 250 volts, the voltage at the plate of V_2 has risen to 350 volts.

There is now a difference of voltage between the two plates, resulting in 100 volts across the output transformer. The output voltage across the transformer primary at any instant is the difference in instantaneous voltage between the two plates.

The action over an entire cycle is shown in Fig. 24-17. We'll use a straight characteristic curve to illustrate the push-pull action, even though the actual curve for a circuit is not straight. Also, to simplify matters further, we'll use the same diagram for both tubes. Figure 24-17a shows how the grid-voltage variations produce corresponding plate-current variations.

As the signal on the grid of V_1 , which is represented by the dashed line begins to swing positive, the voltage at the plate of V_1 begins to go less positive. At the same time, the signal on the grid of V_2 begins to go negative and the plate voltage of V_2 begins to go more positive.

The voltages at the plates of the tubes are opposite in polarity to the grid signal and are shown in Fig. 24-17b. At the instant labelled t_0 the two tube currents are the same, and there is no voltage difference between the two plates. The output voltage shown in Fig. 24-17c is zero. At the instant t_1 , the voltage difference between the two plates is E , and the voltage output at that instant is also E , as shown in c of the diagram. At instant t_2 , the voltage difference between the plates is again zero, and the output voltage is zero. In the interval from t_0 to t_2 , the plate voltage of V_2 is higher

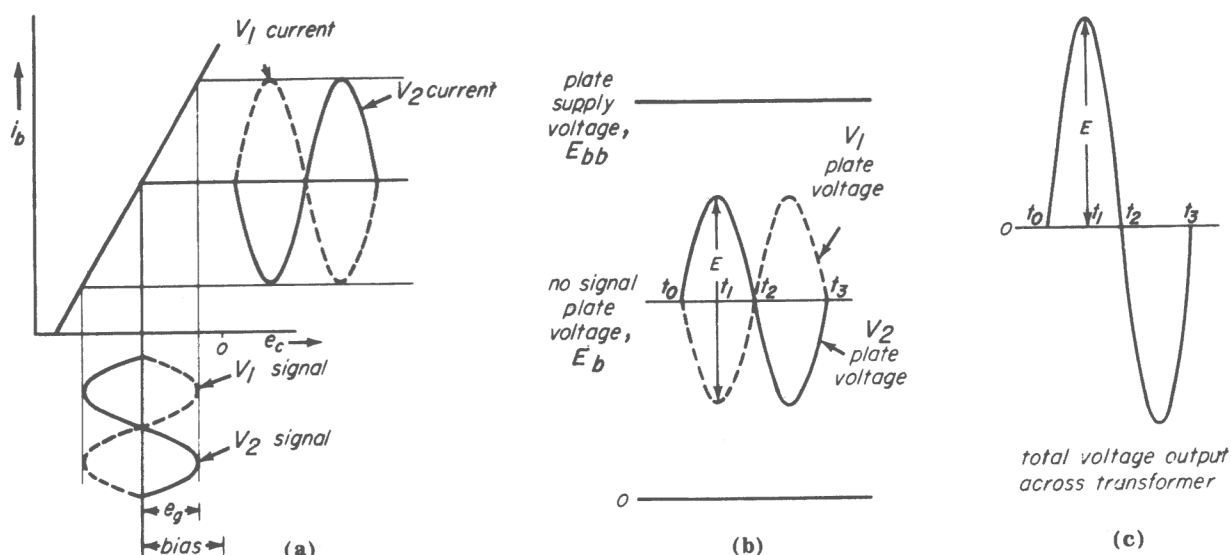


Fig. 24-17

than that of V_1 . In the next half cycle, from t_2 to t_3 , the plate voltage of V_1 is higher than that of V_2 , and therefore the polarity of the output voltage reverses, as shown in c of the figure. The peak voltage across the primary is twice that of a single tube.

Of course, the drawing in Fig. 24-17 is based on imaginary characteristic curve — one that is perfectly straight. Figure 24-18 shows the same process on a typical triode characteristic curve. You can see that when the signal on the grid of either tube is of a polarity that caused the tube to be operating on the lower part of the i_b - e_c curve, the out-

put is distorted, as in Fig. 24-18a. The voltages at the plates of the tubes are shown in b of the figure.

Just as in the previous discussion based on Fig. 24-17, the difference in voltage between the plate of V_1 and V_2 is the voltage impressed across the primary of the output transformer.

Figure 24-18b starts at a point where there is zero signal plate voltage and then shows the voltage at the plate of V_2 rising to its positive peak. Meanwhile, the voltage on the plate of V_1 is going down as far as the characteristic of the tube will allow. The

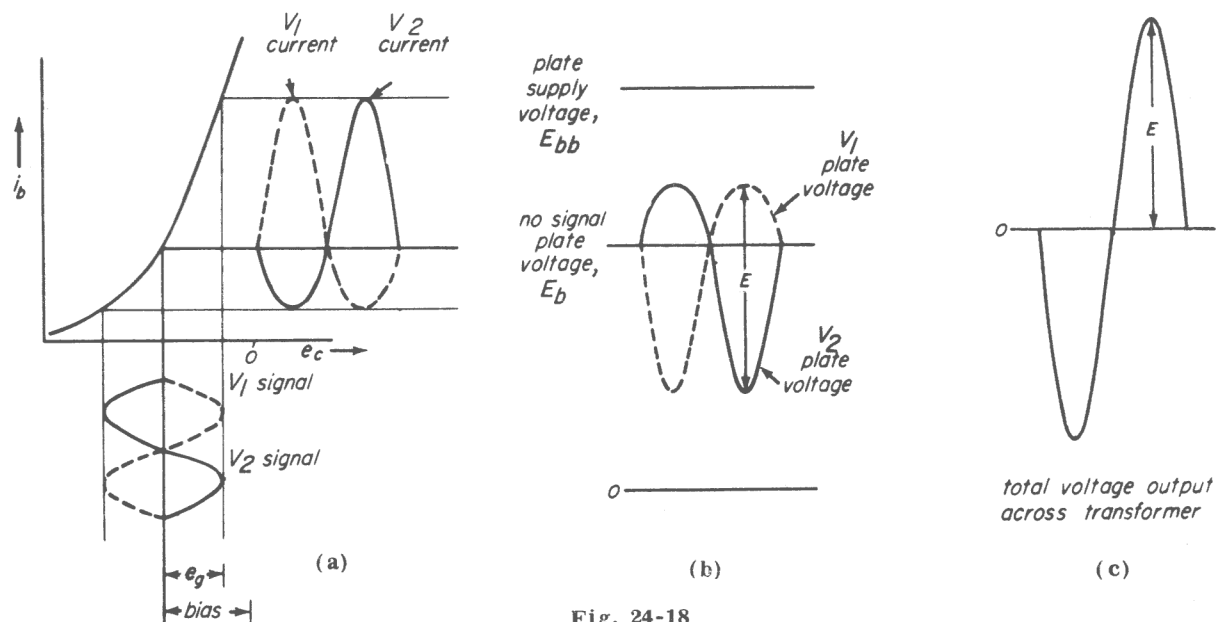


Fig. 24-18

point where the plate voltage of V_2 has reached its peak and the plate voltage of V_1 has reached its maximum negative value is the point of peak voltage of the first half cycle of voltage across the transformer, as shown in Fig. 24-18c. When the polarity of the plate voltages on the tubes reverses, the polarity of the voltage on the output transformer reverses, thereby producing the second half cycle across the transformer.

Because the distortion is reduced, a bigger signal can be applied to each tube in push-pull than could be applied to each tube alone; therefore more than twice the power output of a single tube can be obtained with a push-pull circuit.

Some distortion still remains in the output circuit because the push-pull circuit only cancels out even-harmonic distortion; that is, the second and fourth, etc, harmonic components of the distorted wave. Odd harmonic components of the distortion still remain.

However, because the second harmonic component is the largest, its removal contributes greatly to the over-all sound quality.

The manner in which second and other even harmonics are cancelled out can be seen by studying Fig. 24-19. This figure shows a distorted output wave, due to the non-linearity of the characteristic curve. As previously explained in an Appendix to Lesson 23, the fundamental and second harmonic components of this wave are as shown in *b* of this figure. The d-c component is omitted here for clarity.

The output of each half of the push-pull circuit contains this distorted wave, and its harmonic components. The distorted output wave of V_1 and its fundamental and second harmonic are shown in *a* of the figure. The distorted output of V_2 and its harmonics are shown in *b* of the figure. Note that the output and the fundamental component of V_1 are 180 degrees out of phase with the output and fundamental of V_2 , because the input

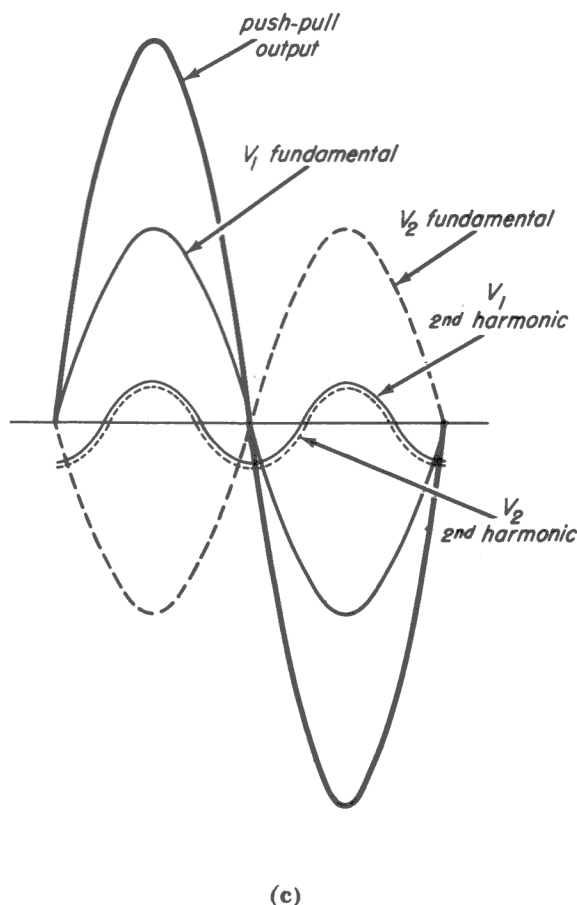
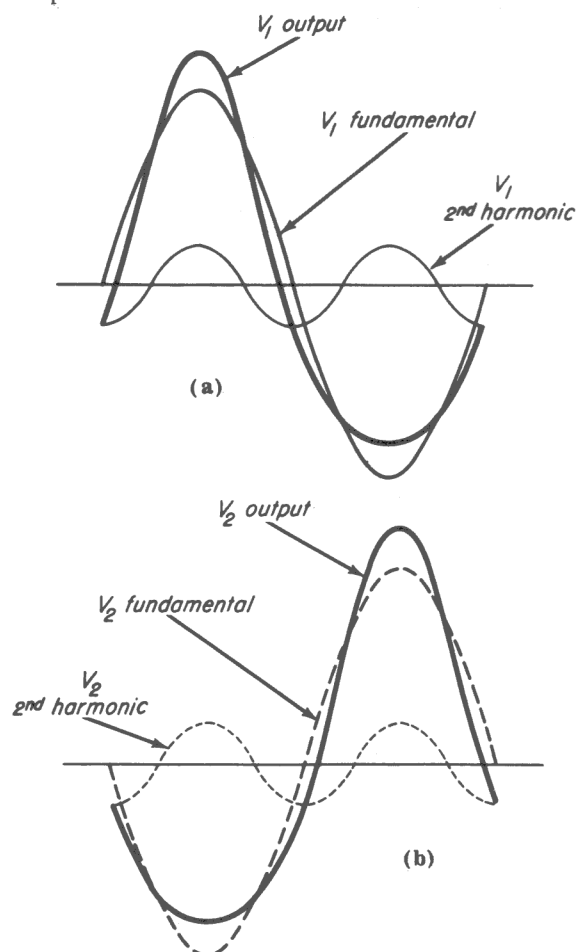


Fig. 24-19

signals to the two tubes are 180 degrees out of phase. This phase relationship is the essential part of the push-pull action. Remember from the discussion of Fig. 24-16 that the output from this circuit depends upon the *difference* in voltage between the two plates. When the plate voltage of one tube rises above the d-c value, the plate voltage of the other tube goes below its d-c value, thus producing the output voltage. The fundamental and second harmonic of each tube are shown combined in *c* of the figure. Note that the fundamentals are out of phase, thus producing a *difference* in instantaneous voltage at each plate, and, therefore, an output voltage. However, the second-harmonic components are in phase; thus, both plate voltages go up and down together at the second-harmonic frequency. There is no difference voltage between the two plates at the second-harmonic frequency, and, therefore, no output at the second-harmonic frequency.

The output signal is transferred to the speaker-voice coil by the output transformer, which performs its usual function of impedance matching.

The plate currents of both tubes combine in the B+ supply and in the cathode resistor. Since one current decreases while the other increases, and vice versa, the total audio-current variations in the power supply and through the cathode resistor are minimized. This simplifies power-supply filtering and bypassing the cathode resistor. The cathode bypass capacitor may be omitted without causing degeneration, although it may be included in some amplifiers to bypass the second-harmonic components of the plate current, which are not cancelled in the cathode circuit.

If one of the push-pull output tubes is removed, the other stage will continue to operate and supply audio output to the speaker. This fact is useful when attempting to localize hum or distortion in the output.

Class B Push-Pull Operation. Because the distortion in the output of a power tube is considerably reduced in push-pull opera-

tion, it is not necessary to limit the operation of the tubes to the linear portion of the characteristic curve. We can bring the bias of the tubes to the point where they operate in lower curved section as well as the linear portion of the characteristic. For example, in class B push-pull operation, the tube is biased to plate-current cutoff or very close to cutoff. Therefore, each tube passes current for only one half cycle, with one tube conducting for one alternation and the other tube conducting for the next alternation. Each tube amplifies one half the signal cycle, and the output signal voltage is applied across one half of the transformer primary for one alternation and across the other half of the primary on the next alternation. The half-cycle output of each tube is combined in the output transformer to produce a full a-c cycle. Since each tube now handles only a half-cycle of the input voltage, twice as much signal can be applied as in class A, resulting in still greater power output.

In class B operation, the grid voltage is usually allowed to go positive. Therefore, some electrons will be attracted to the grid. The grid draws current and the grid circuit consumes power. This power must come from the stage supplying signal to the push-pull grids, which is called the *driver* stage. To obtain this power most efficiently, there is an impedance-matching device, usually an interstage transformer, between them. A transformer used for such coupling is usually called a class B driver transformer and has a step-down impedance ratio from primary to secondary.

Because plate current flows only when a signal is applied to grid, the plate efficiency of a tube operated class B is much greater than for a class-A operated tube. Efficiencies from 60 to 65 percent are obtained. However, because of the great swings in plate current, the B power supply should have better regulation than for a class A amplifier. While the d-c plate current flows in opposite directions in each half of the output transformer primary, at any one instant current flows only in one half of the primary. Therefore cancellation of the d-c component of the magnetic flux does not take

place. Class B amplifiers therefore require output transformers with much larger iron cores.

A class B power amplifier delivers more power than is actually needed for the audio system of a home radio or television receiver. Its use is generally limited to public address systems and broadcast transmitters.

Class AB Operation. As you know, when tubes are biased so that they operate between class A and class B, when plate current flows for more than half a cycle and less than the entire cycle, we say that they are operated class AB. If the peak signal voltage drives the grid positive, the class of operation is AB_2 and if the grid does not go positive, the class of operation is AB_1 . Class A-B operation provides plate efficiencies of from 50 to 60 percent.

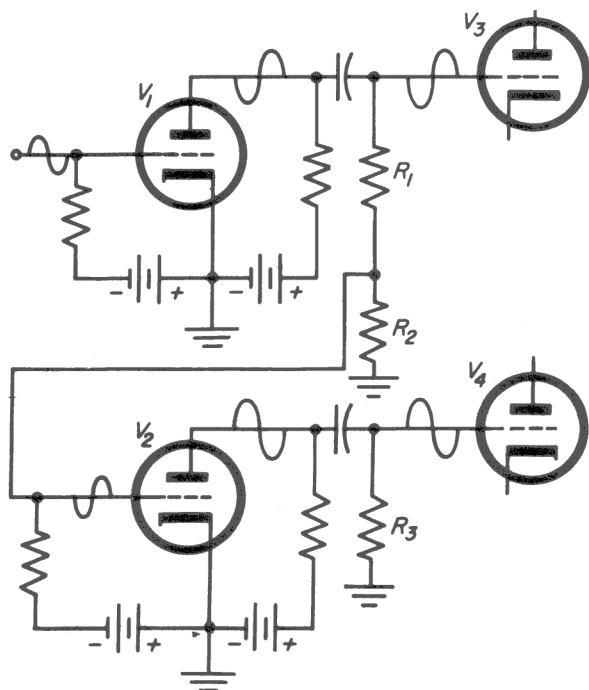
Comparison of Types of Push-Pull Operation. Of all types of push-pull audio power amplifiers, class A provides the least total distortion. For this reason it has become the standard of excellence for high-fidelity power amplification. Class A push-pull amplification has the least plate efficiency of any type of push-pull operation. However, the power supply for such an amplifier does not need the regulation required of one that supplies a class AB or B amplifier. Class AB amplifiers provide greater power output and greater plate efficiency than class A amplifiers. Greater driving voltages can be applied to class AB amplifiers than to class A, but less than to class B amplifiers. If grid current flows (class AB_2), the driver stage must supply power to the grid circuit. While a class AB amplifier tends to cancel out even harmonics, as in class A operation, the odd harmonics, particularly the third harmonic, may be unpleasantly high. Class B operation provides greater power output and greater plate efficiency than either A or AB operation. However, class B operation requires greater input signal voltage and power from the driver stage and greater voltage regulation in the power supply than does class AB.

Push-Pull Pentodes and Beam-Power Tubes. Pentodes and beam-power tubes may be operated in push-pull in much the same way as triodes. The advantage of using pentodes is in the fact that they have greater power sensitivity than triodes, and, for a given power output, require less driving voltage than do triodes. However, they introduce more odd-harmonic distortion than triodes do.

24-6. PHASE INVERTERS

The two tubes of the push-pull circuit each require a signal that is 180 degrees out of phase with the other. While transformers have been widely used to provide these out of phase signals the present practice is to use another method of coupling and do away with the transformer. Unless the interstage transformer is well designed, large, and (usually) expensive, it introduces distortion, which the push-pull operation of the output tubes *does not cancel out*. The use of interstage coupling transformers cannot be avoided in class B and AB_2 operation where a low-impedance source of driving signal is needed. The type of circuit that takes the place of the interstage audio transformer is called a *phase inverter*. There are many varieties of phase-inverter circuits in use today, but all of them work because of either the 180-degree phase reversal that occurs in a electron tube between grid and plate voltage or the 180-degree phase difference between the plate and cathode voltages.

Figure 24-20 shows the basic principle of the first method. The signal that appears on the plate of V_1 is 180 degrees out of phase with the signal at its grid. This signal voltage is passed on to the first of the push-pull power tubes, V_3 . The grid resistors of V_3 , R_1 and R_2 , act as a voltage divider. A portion of the signal that goes to the grid of V_3 is fed also to the grid of V_2 . The signal is inverted in V_2 so that the signal passed on to the grid of the second of the push-pull power tubes, V_4 is 180 degrees out of phase with that fed to V_3 . It is important that the two push-pull tubes have signal inputs of equal amplitude, since the operation of the



basic phase inverter circuit

Fig. 24-20

circuit depends upon each tube having equal and opposite signal currents in the plate circuit. If the gain of V_2 were 60, and the output of V_1 were fed back directly to V_2 , one push-pull tube would have 60 times as much signal as the other. Therefore, the input to V_2 is reduced by the voltage divider composed of R_1 and R_2 . The values of these resistors are chosen so that the voltage across R_2 is reduced by the amount of gain that V_2 has. The sum of $R_1 + R_2$ usually equals the value of the grid resistor, R_3 . The values of R_1 and R_2 are selected so that the voltage across R_2 (which is fed to the grid of V_2) is equal in value to the voltage fed to the grid of V_1 .

The second basic principle is illustrated

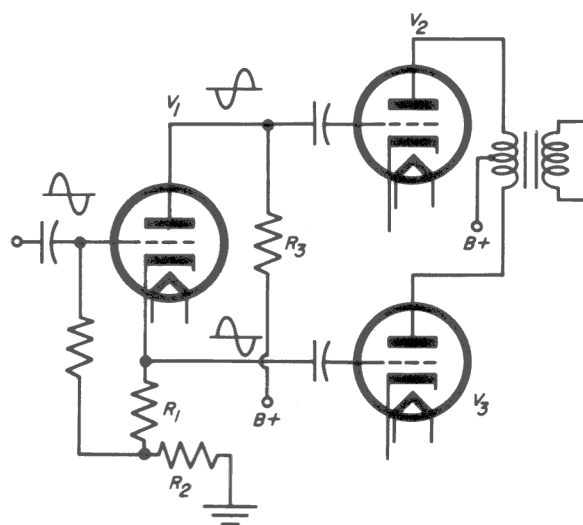


Fig. 24-21

in Fig. 24-21. Tube V_1 is a *phase splitter*, or *degenerative phase inverter*. In this circuit, equal plate and cathode loads are used. As shown by the waveform on the diagram, the voltage fed to the grid of V_2 is always 180 degrees out of phase with that fed to the grid of V_3 , and these voltages are equal because the loads are equal. In this circuit, R_1 and R_2 act as a d-c voltage divider, with the value of R_1 being selected so that the d-c voltage across it is the required bias voltage for the grid of V_1 . The sum of $R_1 + R_2$ is the total cathode load, and that is made as nearly equal to R_3 , the plate load, as commercial resistor values allow.

The circuit of Fig. 24-21 requires only one tube, but no gain is obtained from the phase-inverter stage due to the unbypassed cathode load. Also, because the cathode of this tube cannot be bypassed to ground, it is more susceptible to hum pickup from the heater in the tube.